# New Muon Lifetime and the Fermi Coupling Constant $G_F$

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HallC meeting, JLAB, Aug 10, 2007

# Precision Muon Phyiscs

"Of all the recent muon experiments, the measurement of the muon anomalous magnetic moment, $a_\mu=(g_\mu-2)/2$ by experiment E821 at BNL stands out both experimentally and theoretically. "

"That measurement was statistics limited and could be further improved. Indeed, an upgrade proposal by the  collaboration outlines a plan to reduce the error in  by a about factor of 2."

# Precision Muon Phyiscs

MUONS

- PSI
- TRIUMF
- BNL
- FNAL ?

| | |
|---|---|
| Michel parm | $\rho, \delta, \eta, P_\mu\xi$ |
| Lifetime | $G_F$ (1 ppm) |
| $\mu^-p$ capture | $\Lambda_S \rightarrow g_P$ |
| $\mu^-d$ capture | L1A |
| g-2 | SUSY, BSM |
| $\mu A \rightarrow eA$ | LFV, BSM |

# MUON Physics

- **Physical Review Letters, 20 July 2007,Volume 99, Number 3**
  - **Improved Measurement of the Positive-Muon Lifetime and Determination of the Fermi Constant**
    D. B. Chitwood *et al.* (MuLan Collaboration)
    Published 16 July 2007
  - **Measurement of the Muon Capture Rate in Hydrogen Gas and Determination of the Proton's Pseudoscalar Coupling *gP***
    V. A. Andreev *et al.* (MuCap Collaboration)
    Published 16 July 2007
    032002
  - **Electroweak Radiative Corrections to Muon Capture**
    Andrzej Czarnecki, William J. Marciano, and Alberto Sirlin
    Published 16 July 2007
    032003

| Standard Model Electroweak Interaction (4 parameters) | | | |
|---|---|---|---|
| g' U(1) | g SU(2) | $M_H$ (Higgs) | $v$ expectation value of the Higgs field |

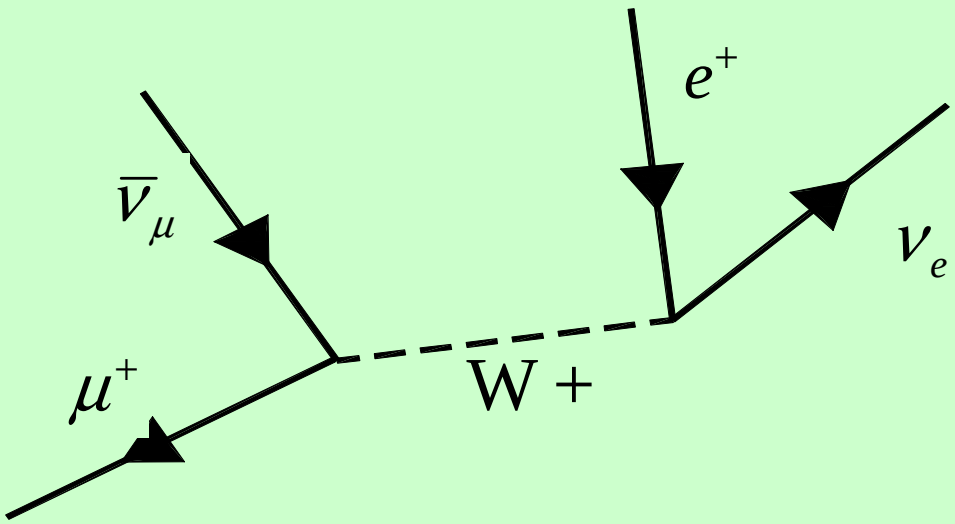
| | | |
|---|---|---|
| $\alpha$ | Fine structure constant | 00.045 ppm |
| $G_F$ | Fermi coupling constant | 09.000 ppm |
| $M_Z$ | Mass of the Z boson | 23.000 ppm |
| $M_H$ | Higgs mass | constrained |

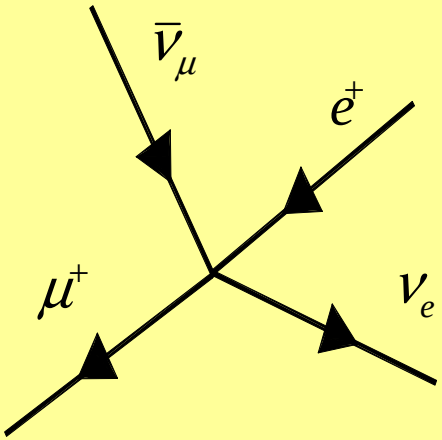
| |
|---|
| $m_i$ masses of quarks and leptons (12) |
| CKM quark mass mixing matrix, [Cabbibo] Kobayashi-Maskawa (4) |
| MKS mass matrix for neutrinos, Maki-Nakagawa-Sakata matrix (4) |
| Cosmological Constant (1) |
| QCD Coupling (1) |
| 26 dimensionless constants for standard model |

- Ritenbergen and Stuart, Nucl. Phys. B564 (2000)
- PDG, Particle Data Group

# Electroweak Interaction

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



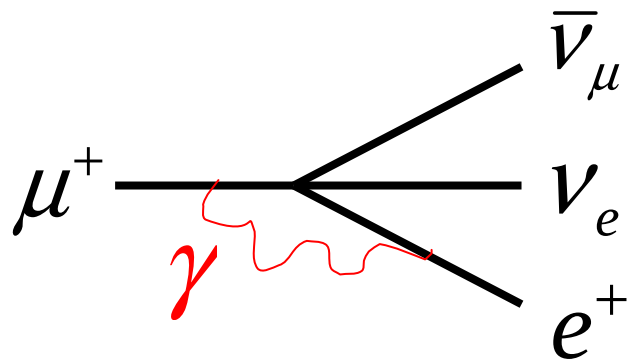

$$L_F = -\frac{2\sqrt{2}G_F}{4}\left(\bar{u}(\nu_e)\gamma^\alpha(1-\gamma_5)u(e^+)\right)\left(\bar{u}(\bar{\nu}_\mu)\gamma^\beta(1-\gamma_5)u(\mu^+)\right)$$

$$L_W = -\frac{g^2}{8}\left(\bar{u}(\nu_e)\gamma^\alpha(1-\gamma_5)u(e^+)\right)\frac{-g_{\alpha\beta}+\frac{k_\alpha k_\alpha}{M_W^2}}{k^2-M_W^2}\left(\bar{u}(\bar{\nu}_\mu)\gamma^\beta(1-\gamma_5)u(\mu^+)\right)$$

$$L_W = -\frac{g^2}{8}\left(\bar{u}(\nu_e)\gamma^\alpha(1-\gamma_5)u(e^+)\right)\frac{g_{\alpha\beta}}{M_W^2}\left(\bar{u}(\bar{\nu}_\mu)\gamma^\beta(1-\gamma_5)u(\mu^+)\right)$$

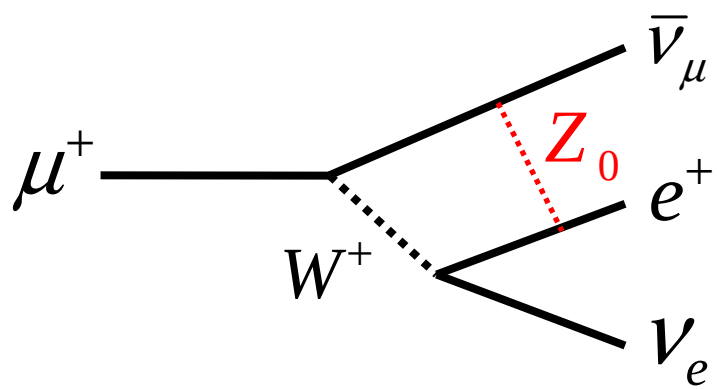
# Fermi Coupling constant

$$\frac{1}{\tau} = \frac{G_F^2 m_\mu^5}{192\pi^3}\left(1 + \delta\right)$$




+ …

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}\left(1 + \Delta r\right)$$




+ …

The theoretical uncertainty on $G_F$ *as extracted from the muon lifetime is < 0.3 ppm.*

# ELectroweak

- Basic parameters [2006] (e.g. PDG)

| Standard Model Electroweak Interaction | | |
|---|---|---|
| $\alpha$ | Fine structure constant | 00.045 ppm |
| $G_F$ | Fermi coupling constant (Before current effort) | 09.000 ppm |
| $M_z$ | Mass of the Z boson | 23.000 ppm |

$$\frac{\delta G_F}{G_F} = -\frac{1}{2}\frac{\delta\tau}{\tau} - \frac{5}{2}\frac{\delta m_\mu}{m_\mu} - \frac{1}{2}\frac{\delta(1+q)}{(1+q)}$$

9 ppm 0.08 ppm 0.3 ppm

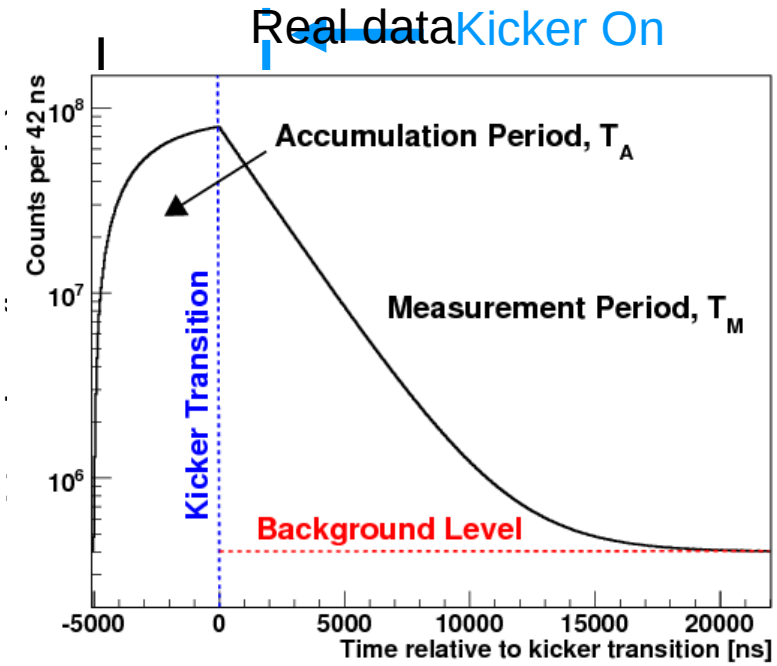
# MuLan Collaboration

University of Illinois at Urbana Champaign (UIUC)
Boston University (BU)

University of California, Berkeley (UCB and LBNL)
University of Kentucky, Lexington
TRIUMF, Vancouver
James Madison University, (JMU)
KVI Groningen, Netherlands
Istanbul Technical University, Turkey

HallC meeting, JLAB, Aug 10, 2007

# The experimental concept

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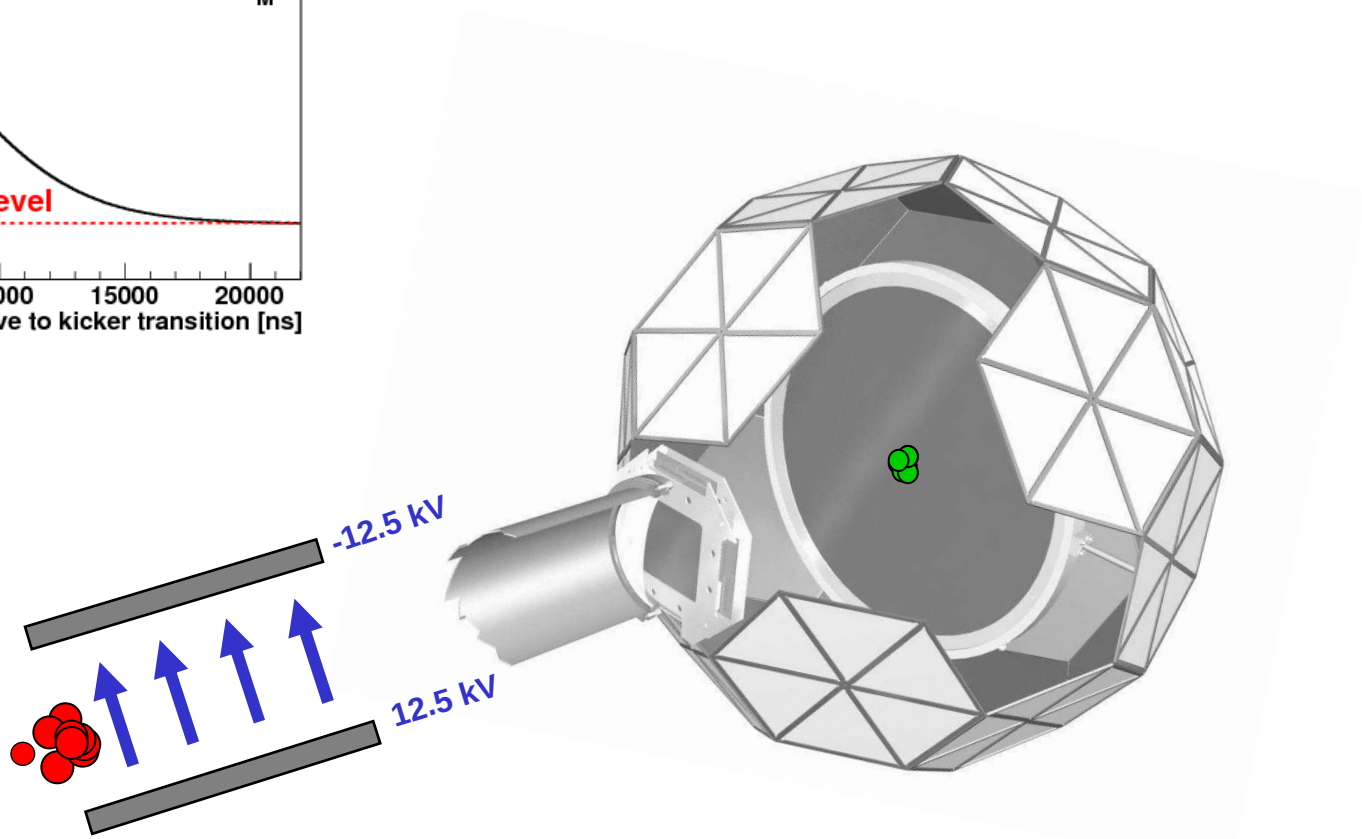


# Rates

- 1ppm requires at least $10^{12}$ observed decays
  - Probability for a set of measurements ($t_1$, $t_2$,…)

$$dP(t_1, t_2 ... | \tau) = \rho(\, t_1 \,|\, \tau \,)\rho(\, t_2 \,|\, \tau \,)...dt_1 dt_2 ...$$

  - Probability that a parameter has a value based on (t1, t2,…)

$$L(\tau \,|\, t_1, t_2 ...) = \rho(\, t_1 \,|\, \tau \,)\rho(\, t_2 \,|\, \tau \,)$$

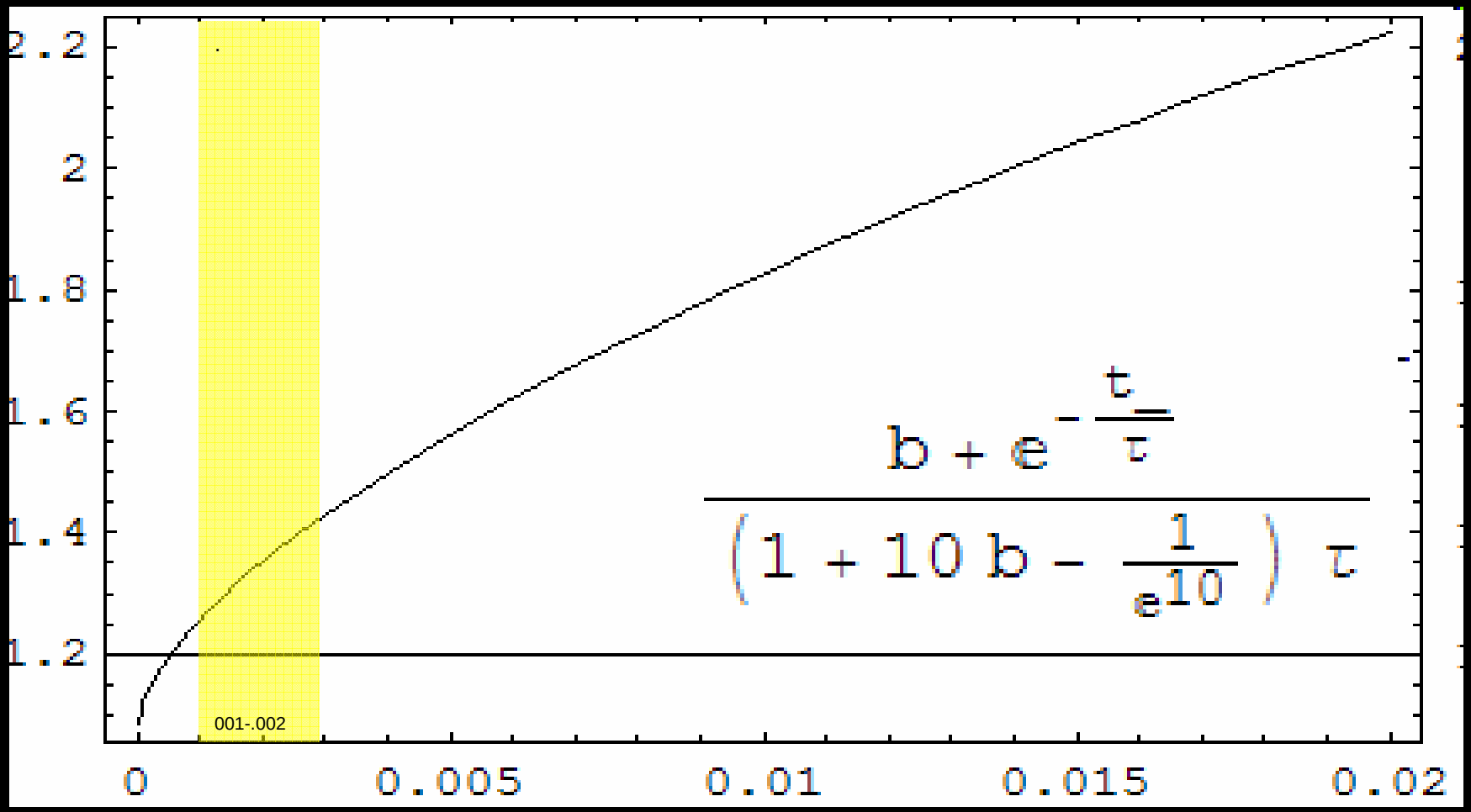
# Rates and Uncertainty

- For a simple distribution one can find the value for $\tau$ that make the experimental result highly probable and estimate the uncertainty. (same result from fitting)

| | |
|---|---|
| $\frac{dL(\tau \mid t_1, t_2 \ldots)}{d\tau} = 0$ <br> $\rho(t) = \frac{1}{\tau} e^{-\frac{t}{\tau}}$ <br> $\tau = \frac{t_1 + t_2 + \ldots}{N}$ | $\Delta\tau = \frac{\left[\int \frac{1}{\rho}\left(\frac{\partial\rho}{\partial\tau}\right)^2 dt\right]^{-\frac{1}{2}}}{\sqrt{N}}$ <br> $\Delta\tau = \frac{\tau}{\sqrt{N}}$ |

# Uncertainty with Background

Assume measurement period of 10$\tau$



# Uncertainty

- Uncertainty is increased due to new terms in the distribution
- Lifetime is distorted due to an incorrect distribution
  - The average is no longer an unbiased estimator for the lifetime when there is background
- Reduce your uncertainty through statistics therefore an unbiased measurement of t is critical
- Individual precise measurements are not critical

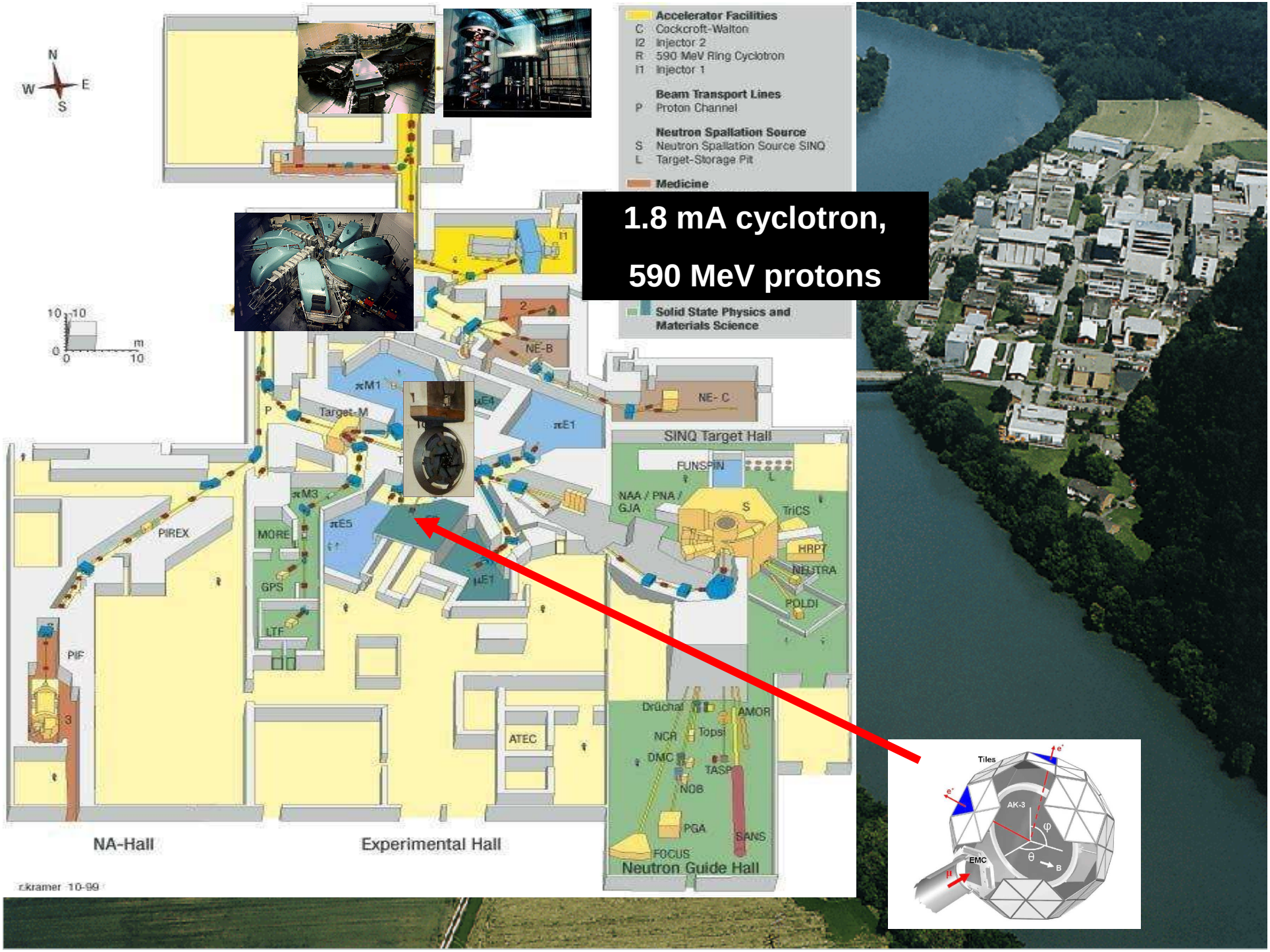
KNOW YOUR DISTRIBUTION

REMOVE SYSTEMTICS

# Rates

- To accumulate the statistics necessary in a one month period
  - $4.0 \times 10^5$ muon decays/sec
  - 1 muon every 3 $\mu s$
- Need more than 1 muon in target at a given time.
  - Granularity (FAST approach)
  - Pulsed beam (μLAN Approach)
    - Duty facor (35 μs -total ) /(5 μs –on) [factor of 7]
  - $3 \times 10^6$ muons/sec

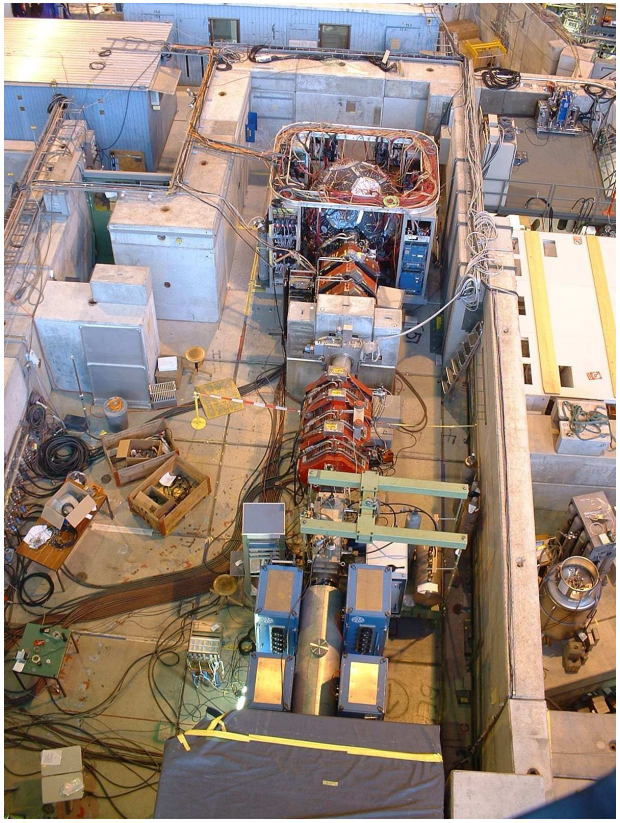
Beam rate of a FEW MHz

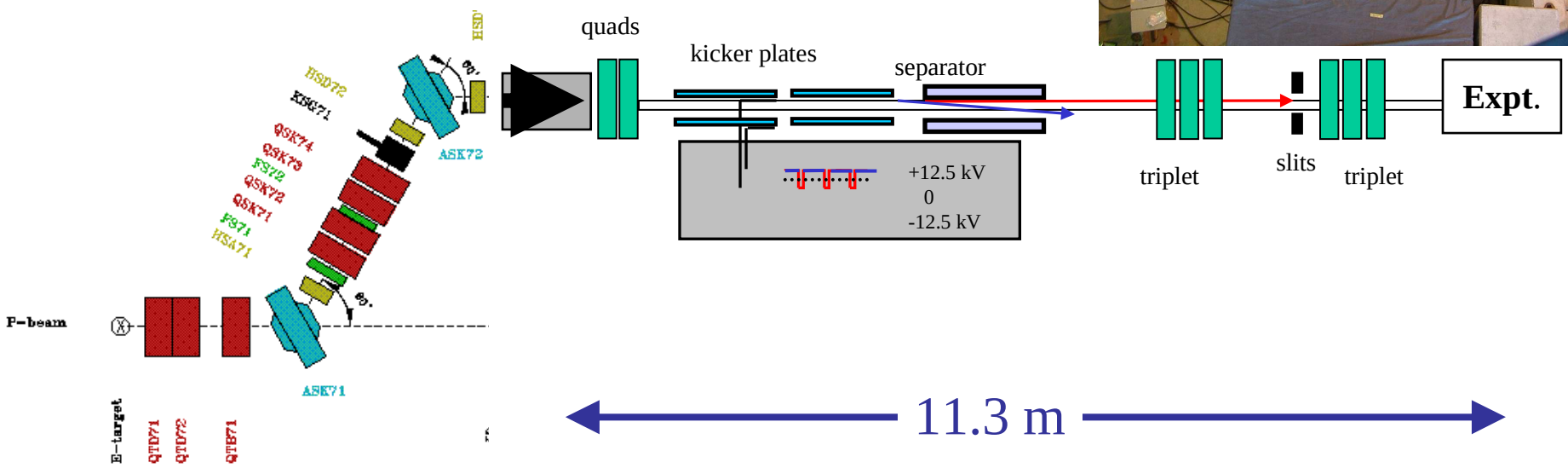

1.8 mA cyclotron,
590 MeV protons
Accelerator Facilities
C Cockcroft-Walton
I2 Injector 2
R 590 MeV Ring Cyclotron
I1 Injector 1
Beam Transport Lines
P Proton Channel
Neutron Spallation Source
S Neutron Spallation Source SINQ
L Target-Storage Pit
Medicine
Solid State Physics and Materials Science
N
W
E
S
NE-B
NE- C
πM1
Target-M
πE1
SINQ Target Hall
FUNSPIN
NAA / PNA / GJA
TriCS
HRPT
NEUTRA
POLDI
πM3
πE5
MORE
GPS
LTF
PIREX
PIF
μE1
ATEC
Drüchal
AMOR
NCR
Topsi
DMC
TASP
NOB
PGA
SANS
FOCUS
Neutron Guide Hall
NA-Hall
Experimental Hall
r.kramer 10-99
Tiles
AK-3
EMC
φ
θ
B

# πe3 beamline

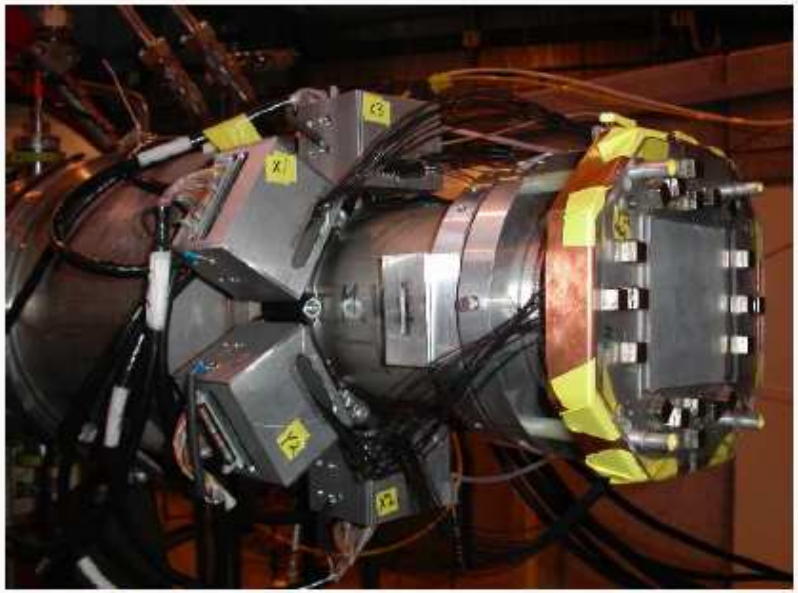
Surface Muon Beam **29 MeV/c**

- Dedicated beam studies for several years
- A **Beam Rate** > 11 **MHz**;
- Spot at target, only few cm2.
- Separator leaves about 5–10% positron background.
- Many elements to tune. Straight beam is tricky.
- Extinction fraction looks reasonable. (1000)

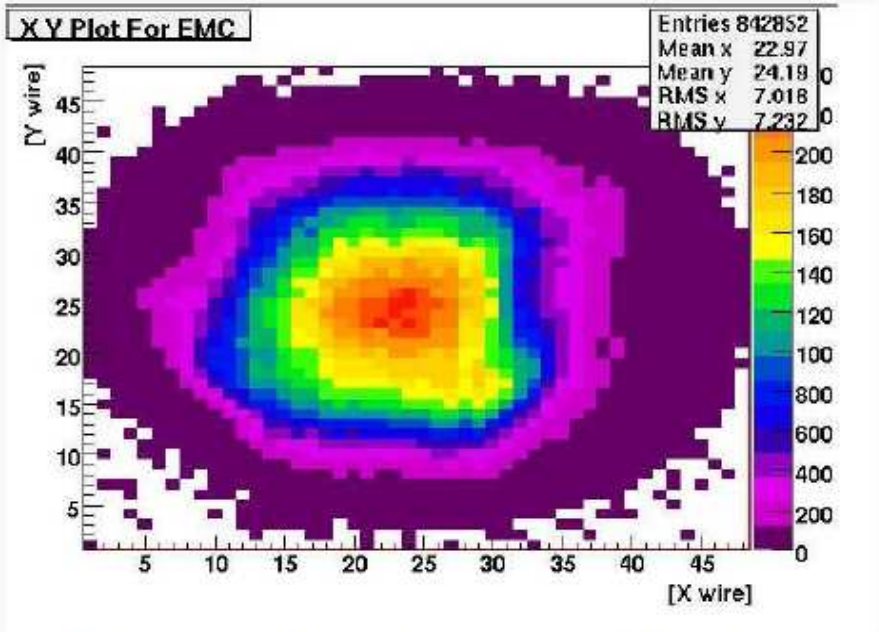




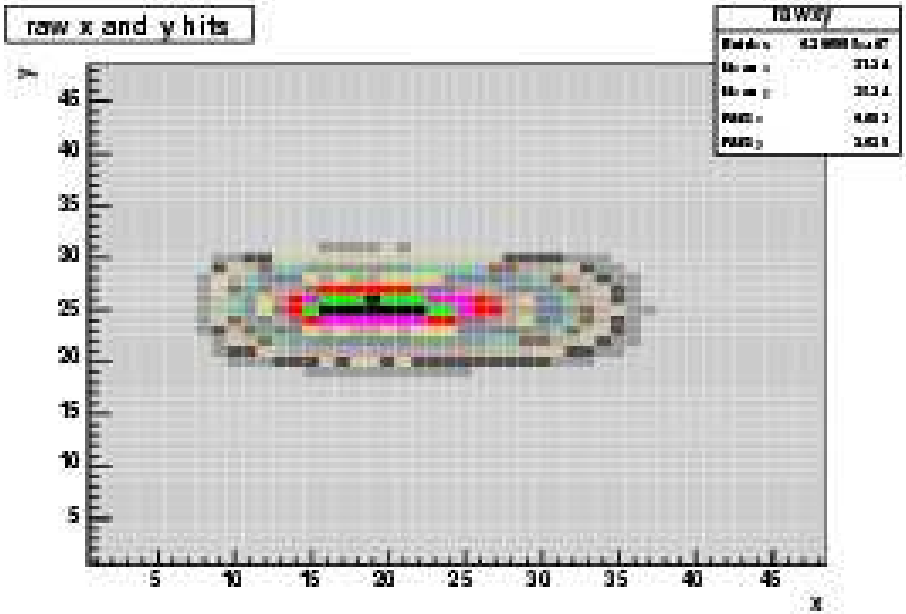
# Entrance Muon Counter

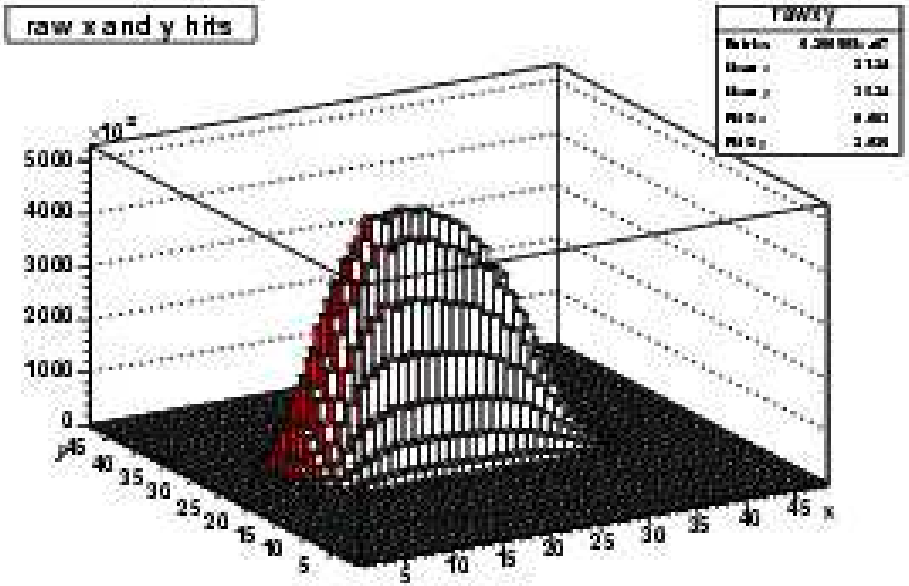


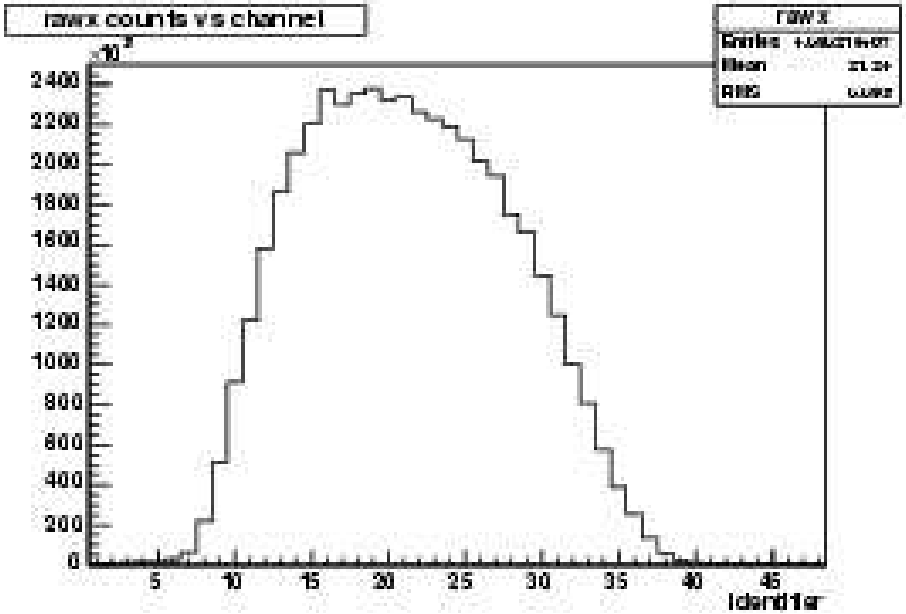
- ✓ 96 active wires on each plane
- ✓ 1 mm spacing
- ✓ reading every two wires
- ✓ resolution: 2 mm

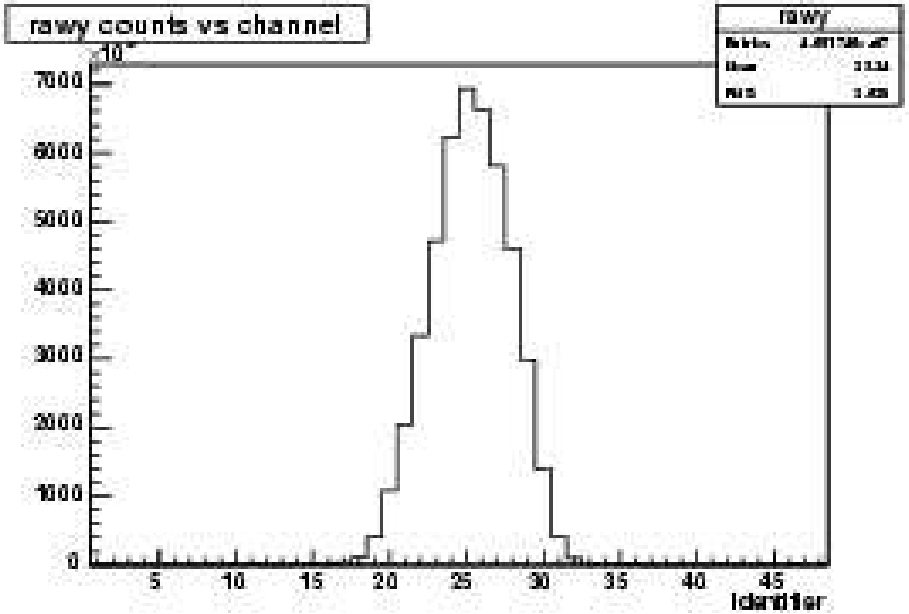


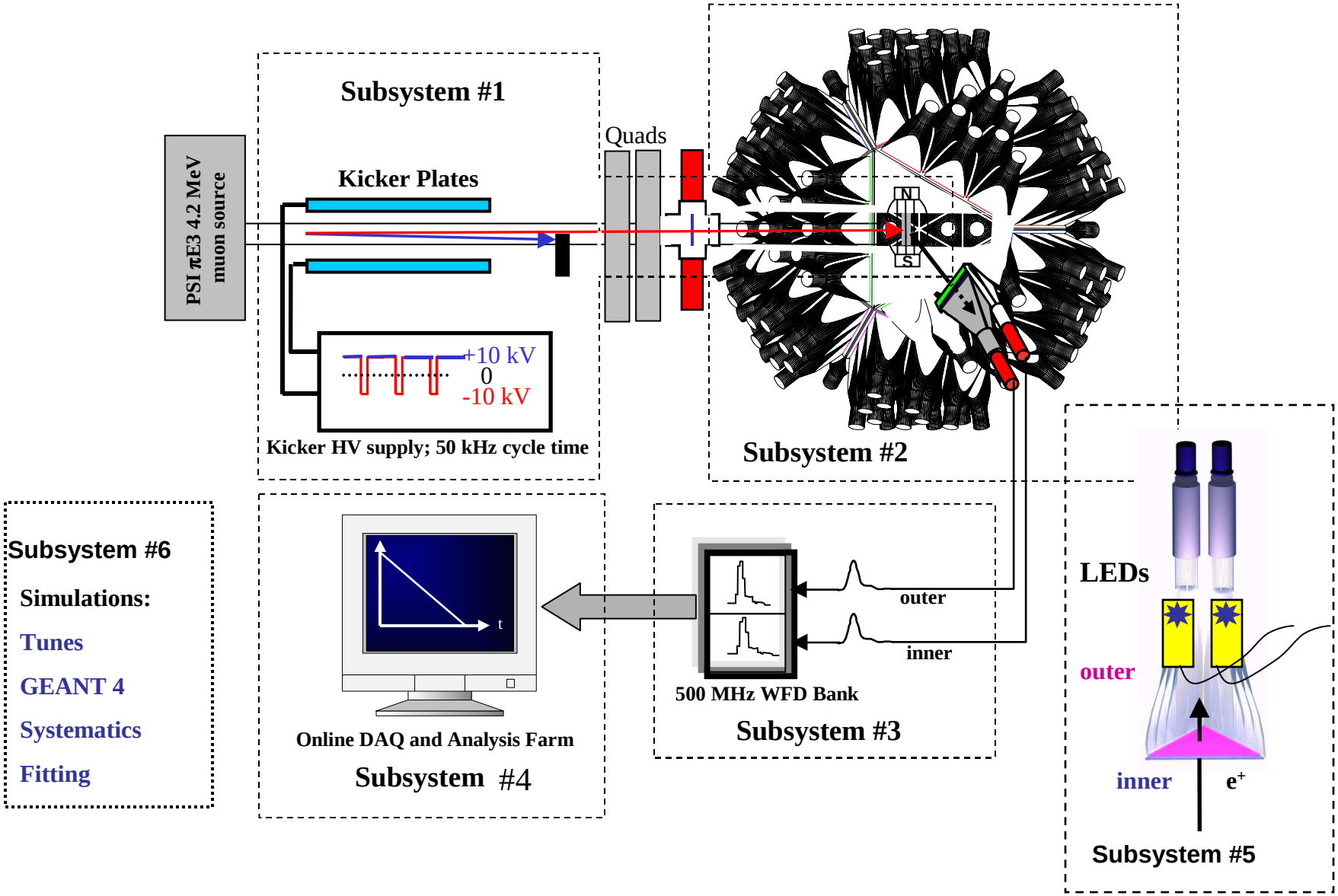

- ✓ Logic pulses between 40 and 100 ns long
- ✓ FPGA for time and position hits
- ✓ Accumulation: Prescaling
- ✓ Measurement: No-prescaling


raw x and y hits
rawxy
y
x

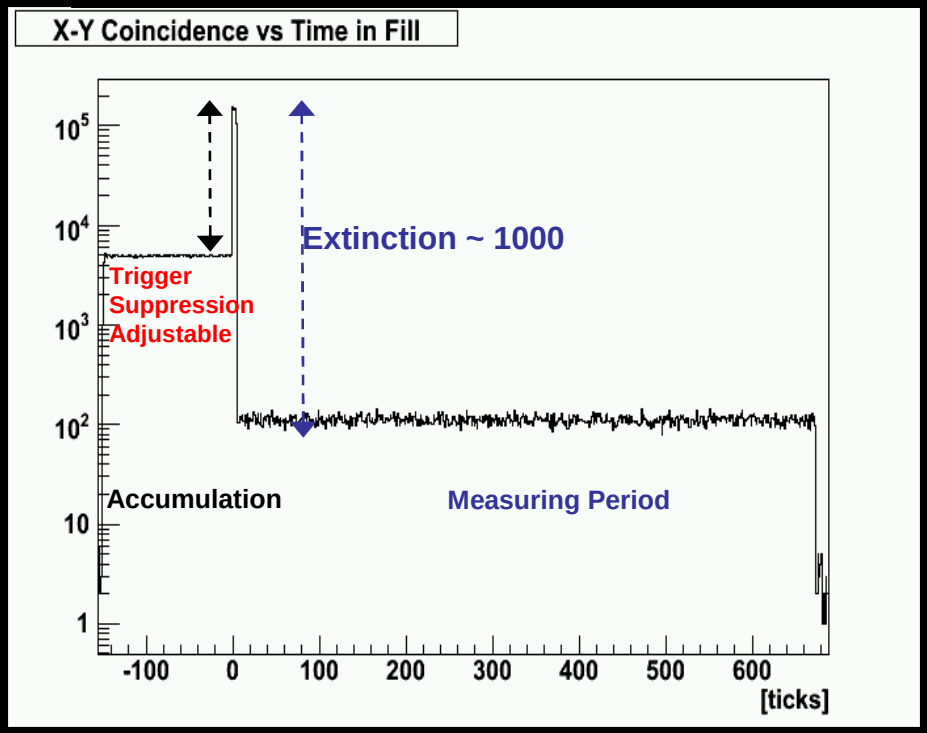

raw x and y hits
rawxy
y
x

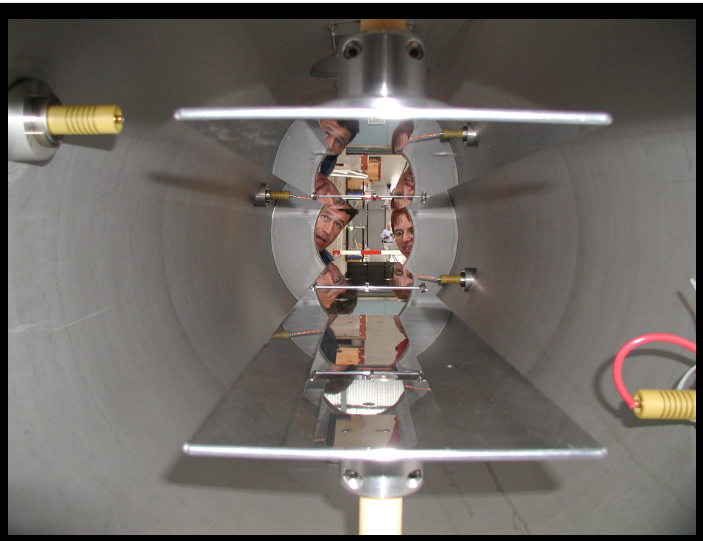

rawx counts vs channel
rawx
Entries
Mean
RMS
Identifier

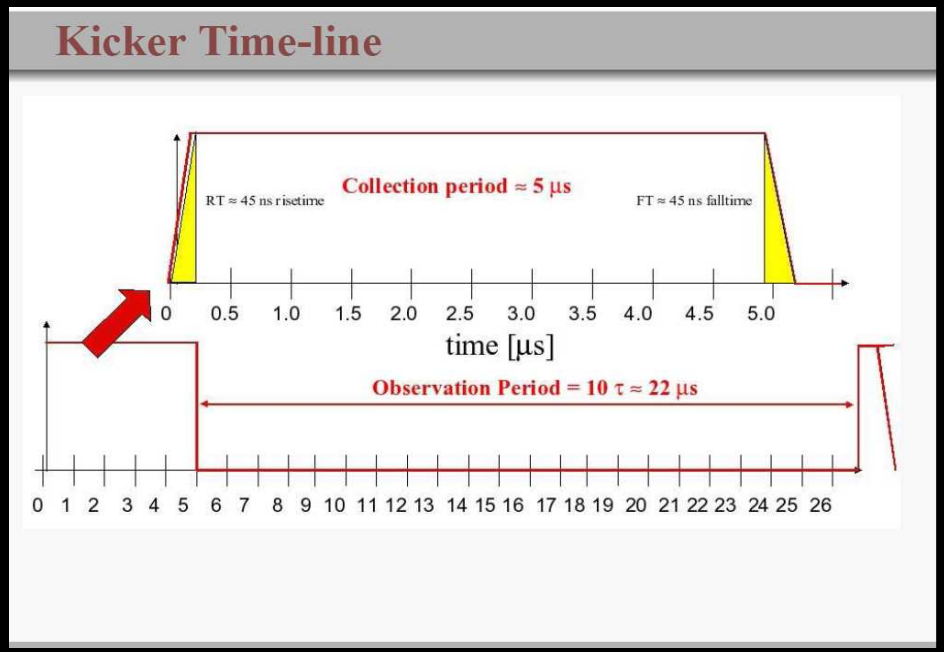

rawy counts vs channel
rawy
Identifier

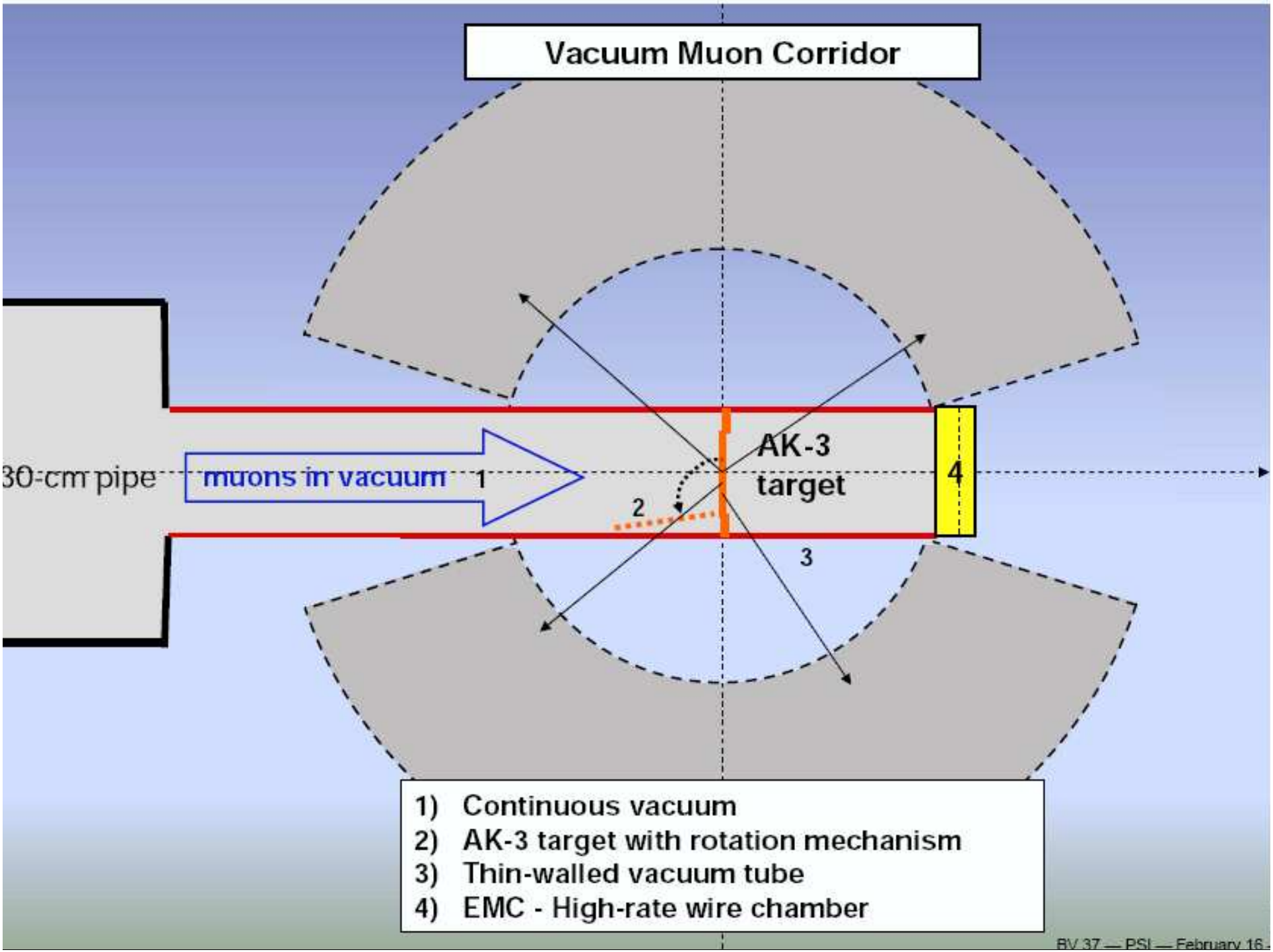

Subsystem #1
PSI πE3 4.2 MeV muon source
Kicker Plates
+10 kV
0
-10 kV
Kicker HV supply; 50 kHz cycle time
Quads
N
S
Subsystem #2
LEDs
outer
inner
e+
Subsystem #5
outer
inner
500 MHz WFD Bank
Subsystem #3
t
Online DAQ and Analysis Farm
Subsystem #4
Subsystem #6
Simulations:
Tunes
GEANT 4
Systematics
Fitting

# 25 kV (+/- 12.5 on each plate) kick, 12 cm gap, 30 kHz: a gift from TRIUMF

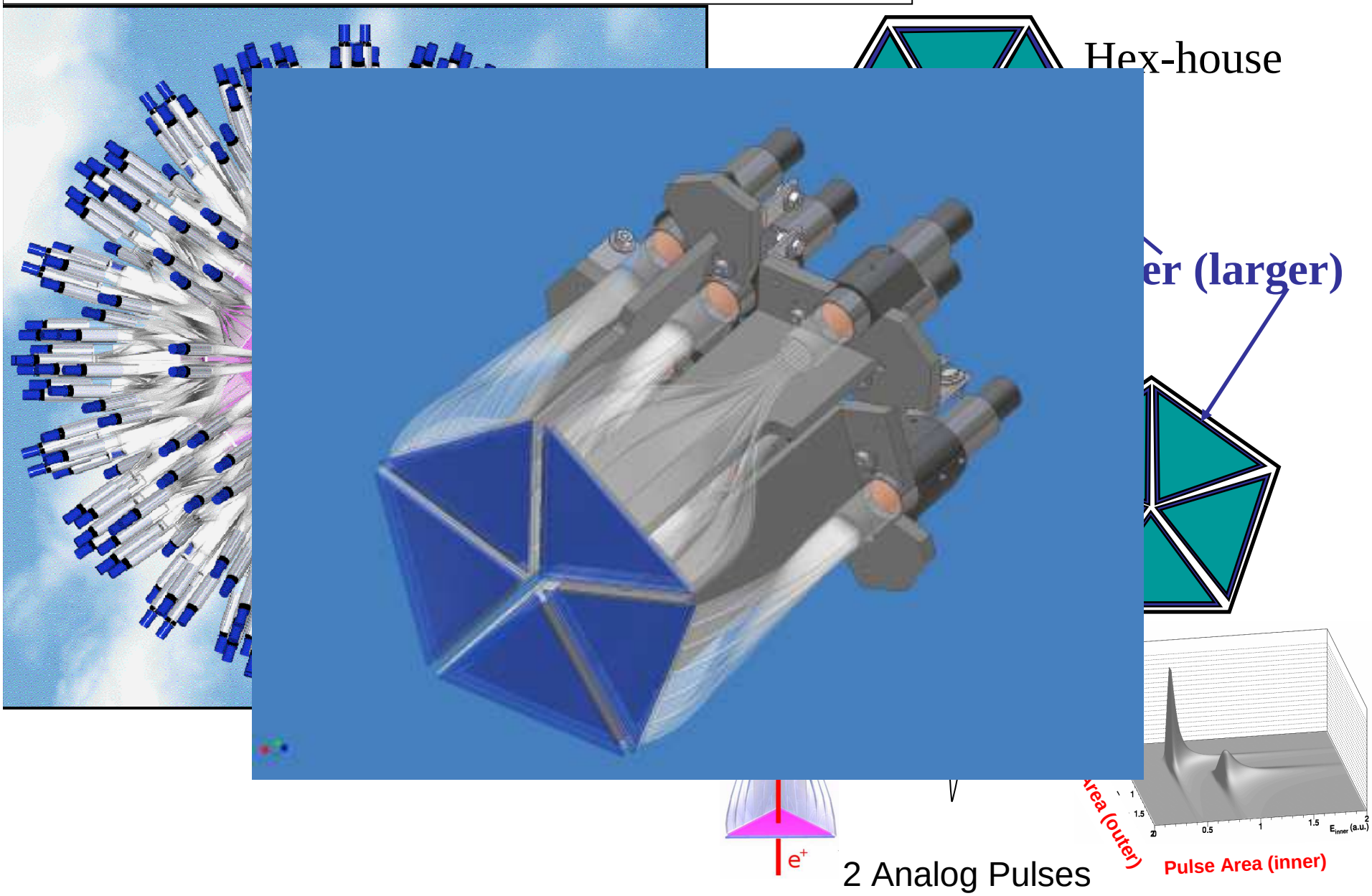


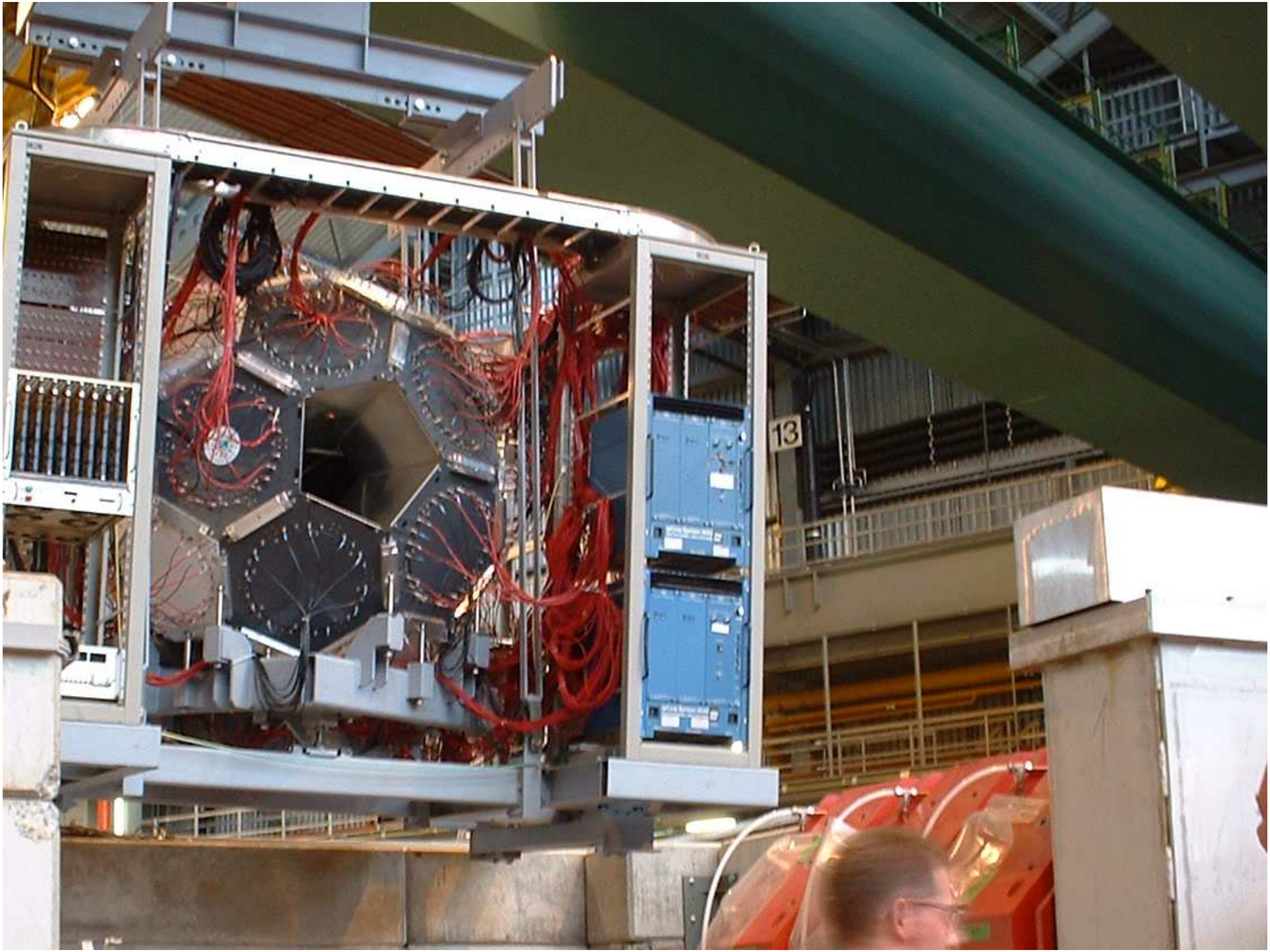





Vacuum Muon Corridor
30-cm pipe
muons in vacuum
1
2
AK-3
target
3
4
1) Continuous vacuum
2) AK-3 target with rotation mechanism
3) Thin-walled vacuum tube
4) EMC - High-rate wire chamber

# 2-sided, soccer-ball geometry

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